OXYGEN AND WATER FROM LUNAR-SURFACE MATERIAL

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ABSTRACT

Analyses of lunar soils returned by the
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tion of oxygen from the lunar-surface material and
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as a habitable base. Five chemical processes are
described in this report: the carbothermic, hydro-
gen reduction, fluorine-exchange, carbonate/oxygen,
and electrolytic reduction processes. Experimental
results are evaluated and problems are identified.

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By W. R. Downs
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SUMMARY

Analyses of lunar soils returned by the Apollo 11 crewmen are indicative that chemically bound oxygen is a major constituent. The extraction of oxygen from the lunar-surface material and the production of water on the moon are processes that must be developed before men can use the moon as a habitable base. Oxygen and water may be produced by means of chemical treatment of the lunar soil. Five chemical processes are described in this report. One process involves the reduction of the lunar-surface material at high temperatures ($1873°$ K or $1600°$ C) with methane; a second process involves the use of hydrogen gas; a third process involves a direct reaction of the soil with fluorine gas; a fourth process involves the conversion of the lunar-surface material to carbonates, which then are acidified to yield carbon dioxide, which is reduced by hydrogen to yield water; and a fifth process involves the direct electrolysis of molten lunar soils to produce oxygen. In all processes, electrolysis is necessary to achieve economic feasibility by means of the recycling of reactants. Some problems that need solution are identified in this report, and the processes that are based on laboratory-bench-type experimental results are assessed. Various areas of scientific research and engineering development are pointed out as cogent to design-information acquisition and optimization of the processes for making oxygen and water on the moon.

INTRODUCTION

Long before his first footprints were made upon the moon, man wondered what might be there. Scientists and engineers pondered the chemical nature of the lunar environment, and they were particularly curious about the physical and chemical characteristics of the lunar surface. Those who were interested primarily in manned exploration speculated that water might be found as primordial ice beneath the layers of lunar dust and that hydrated minerals would constitute the lunar rocks. However, following the Apollo 11 and 12 missions it was disclosed that neither water nor hydrated minerals appeared to be on the surface of the moon. This was a disappointment, because water is man's most valuable mineral. As a consumable, water is of primary concern. Water is vital to man's survival; it is basic to colony support if man is to live on the moon. The availability of water is the potential for spacecraft payload optimization wherever man is to travel into deep space. Space planners realize that oxygen and water availability will determine the feasibility of using the moon itself to

support extended lunar-exploration activities and the feasibility of using an extra-terrestrial body (such as the moon) as a base for the support of an integrated United States space-exploration plan. The members of a permanent colony on the moon or, for that matter, on any planet must live off the land to a large extent. Only then can resupply requirements be minimized. For human existence, the basic chemical element that must be extracted from the moon (or a planet) is oxygen in some usable form. Therefore, the manufacture of oxygen from local surface materials becomes necessary for life support and for rocket-refueling supply. In fact, manned exploration of the solar system can be accomplished by the use of the space hardware that is available currently if sufficient fuel suitable for rocket use can be manufactured on the moon.

Extracting life-sustaining oxygen and water from inorganic lunar-surface material presents an exciting technical challenge. If the fundamental chemical process can be developed for an economically feasible application, it may be possible to colonize an area on the moon equal in size to the western hemisphere of the earth. This report is a discussion of five possible processes for making oxygen and water on the moon from lunar-surface materials. These processes are candidates for further study and development.

THE LUNAR SURFACE AS RAW MATERIAL

The Apollo 11 and 12 vehicles carried geology picks that were to be used to chip rock pieces from jagged rocky ridges. These picks were useless because no rocky ridges were encountered. Instead, the lunar surface at the two Apollo landing sites consisted of loose, unconsolidated material that is similar physically to some earth soils. Meteorites impacting the lunar surface had smashed bedrock into small particles consisting of grit, pebbles, and dust; these particles are called regolith. Where the Apollo 11 crewmen landed on the mare, the regolith is approximately 3 to 6 meters thick, and the regolith is 6 to 10 meters thick where the Apollo 12 crewmen landed. The life-support oxygen and fuel oxidizer that are required for man's extended stay on the moon and for manned exploration of the solar system must be synthesized from the regolith raw material. Thus, an examination of the regolith for its chemical suitability as a raw material is a necessary first step.

A photograph of the dust or fines obtained from the lunar surface is given in figure 1. The range in particle size is from 37 to 250 microns, and the average particle size is 65 microns (ref. 1). The material resembles cement powder in color and texture. A photomicrograph of a thin section of the lunar soil is shown in figure 2. This figure is indicative of the nature of the crystallization and the extent that glass is present; glass binds the individual crystalline materials. Physical analyses of the lunar particles are indicative that approximately 44 percent by volume is crystalline particles, that 4 percent by volume is glass, and that 52 percent is a composite called breccia, which consists of a mixture of crystalline particles and glass. To induce chemical activity of such a mixture of minerals with any reactant, the material must be melted physically, must be dissolved by some agent (put into solution), or must possess a gas-induced solid phase that is of lower melting point than that of the crystalline materials, so that the reaction products can be removed as rapidly as they are formed.

Petrographic and chemical analyses of Apollo 11 lunar-soil samples indicated that the crystalline material largely consists of basaltic fragments, and that the breccia consists of a mixture of pyroxene, feldspar, plagioclase, olivine, ilmenite, and impure siliceous glass that possesses very little alkali but that possesses appreciable amounts of alkaline earth oxides (ref. 1). From this information, it is possible to synthesize, from minerals that are available on the earth, a mixture of dusts that is similar to the lunar-surface fines. The synthesis was performed as follows.

A survey of earth minerals showed that Hawaiian basalt enriched with ilmenite would be similar to the composition of the lunar surface. In fact, X-ray diffraction analyses of Hawaiian basalt are indicative that the major minerals are clinopyroxene, plagioclase, olivine, ilmenite, and approximately 50 percent by weight of glass.[1] The oxide compositions for Hawaiian basalt and for ilmenite were determined by means of X-ray fluorescence analysis and emission spectrography.[2] The analytical results are shown in table I. Then, some Hawaiian basalt and impure ilmenite were crushed and ground separately to a mean grain size of 65 microns. By means of simple calculations, it was shown that when 7.7 percent by weight of ground ilmenite was added to the ground Hawaiian basalt, the resulting mixture was very similar to the composition (determined by oxide analysis) of the Apollo 11 lunar-soil sample. The comparative data are shown in table II. Several kilograms of simulated lunar fines then were prepared for use in laboratory experimentation.

## PROCESSES FOR MANUFACTURING OXYGEN AND WATER

Five chemical processes for separating oxygen from the lunar-surface materials have been identified by the NASA Manned Spacecraft Center. For the most part, these studies have consisted of laboratory-bench-type experiments in which oxygen and water were produced under semicontrolled reaction conditions. Exhaustive studies to define chemical-process-design parameters have not been carried out. The objective of the present studies is to provide a technological base from which detailed engineering optimizations can be undertaken. The five processes are named carbothermic, hydrogen reduction, fluorine exchange, carbonate/oxygen, and electrolytic reduction. Each process is described as follows.

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[1]Dorsey, James; laboratory work performed in the Lunar Receiving Laboratory, NASA Manned Spacecraft Center.

[2]Martin, J. R.; laboratory work performed in the Lunar Receiving Laboratory, NASA Manned Spacecraft Center.

Carbothermic Process

The carbothermic process (ref. 2) involves melting the lunar-surface fines at approximately 1873° K (1600° C) and passing methane through the molten mixture. The process has been studied by a NASA contractor (ref. 2). The fundamental chemical reaction is given by the equation

$$LUNAR\ MATERIAL + CH_4 \rightarrow H_2O + CO + METALS$$
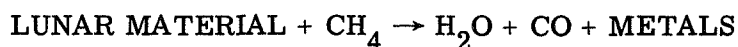
Silica, iron oxide, and titania in the lunar material are reduced at approximately 1923° K (1650° C) to yield water, carbon monoxide, and free metals. In turn, the carbon monoxide must be reacted with earth-supplied hydrogen in the presence of a nickel-kieselguhr catalyst to yield water and methane; then, the methane is recycled. The chemical reaction shown in the following equation occurs readily at 523° K (250° C) and a pressure of 6.18 N/m^2 (6.1 atmospheres).

$$CO + 3H_2 \rightarrow H_2O + CH_4$$
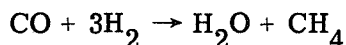
As the methane is recycled, the water is electrolyzed to recover hydrogen and to yield oxygen as a useful product. A flow diagram of the process for the conversion of CO to water and methane is shown in figure 3. As much as 60 percent of the methane is converted to carbon monoxide on the first pass through the melt. The CO yield, based on the amount of carbon charged to the melt, is shown as a function of time in figure 4.

In laboratory tests, it has been difficult to get methane to flow into the melted material. Furthermore, because of the corrosivity of the molten silicates in contact with the crucible walls, the service life of the refractory crucibles has been unsatisfactory. To overcome these difficulties, the carbothermic process may be varied by submerging hollow carbon electrodes in the center of a mass of lunar-surface fines contained in a suitable crucible. By striking an electric arc between the electrodes, the lunar-fines material is melted easily in a region between the electrodes. As the electrodes gradually are separated from each other, controlled melting (induced by the electrical resistance of the molten material) is achieved. Methane or hydrogen then can be passed through the hollow electrodes into the melt. Because melting progresses outward.from the electrodes in the crucible, the container walls are preserved; this permits the minerals to melt in such a way that the molten matrix never contacts the container walls. A sketch of the electric-resistance melting process for the reduction of lunar fines is shown in figure 5. The chemical reactions are as follows.

$$LUNAR\ FINES + C + H_2 \rightarrow CO + H_2O + METALS$$

$$LUNAR\ FINES + C + CH_4 \rightarrow 2CO + 2H_2O + METALS$$
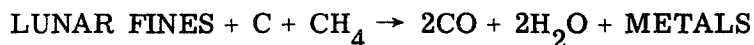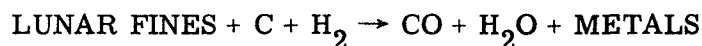
The carbon monoxide is converted to oxygen and carbon by use of the Bosch process, illustrated in figure 6. In the Bosch process, hydrogen is used as a reactant in the presence of an iron catalyst to yield carbon and water. The chemical reaction is as follows.

$$CO + H_2 \rightarrow C + H_2O$$

The carbon may be deposited into usable form for electrodes. The success of the carbothermic process, modified as just described to eliminate the problem of short container life and the difficulty of introducing the methane reactant, depends on the capability of generating high-amperage electrical power on the moon and on the capability to deposit the recovered carbon in an acceptable form for electrodes.

Hydrogen Reduction Process

Hydrogen is an excellent reducing agent for oxides of elements heavier than manganese in the periodic table. For lunar-surface material, this means that iron oxide and the iron portion of ilmenite mineral are reducible by hydrogen. Therefore, a process for reducing lunar soils by the use of hydrogen is being developed at the Manned Spacecraft Center.[3] In this process, solar energy is used to melt small batches of lunar fines into which hydrogen is bubbled; the water is collected by means of condensation. Then, the water is electrolyzed by the use of solar power or nuclear-generated power to obtain oxygen and hydrogen; the hydrogen is recycled in the process. A sketch of the apparatus is shown in figure 7. The fundamental chemical reaction, which occurs between 1273° and 1773° K (1000° and 1500° C), is the following, in which $FeO \cdot TiO_2$ represents ilmenite

$$FeO \cdot TiO_2 + H_2 \rightarrow Fe + H_2O + TiO_2$$
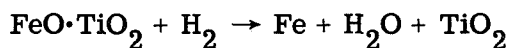
Theoretically, the hydrogen reduction process should yield approximately 0.77 kilogram (1.7 pounds) of water (or 0.70 kilogram (1.54 pounds) of oxygen) for each 45.4 kilograms (100 pounds) of lunar fines treated with 0.090 kilogram (0.2 pound) of hydrogen. In locales of ilmenite-rich fines, or perhaps by the use of magnetically separated lunar fines, the amount of raw material that is required may be reduced appreciably.

As presently conceived, the hydrogen reduction process is a batch-type process in which only relatively small quantities of raw material can be treated at any one time.
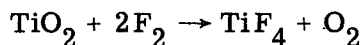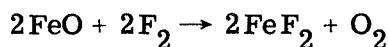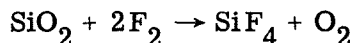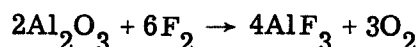
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[3]Patent applied for by A. Sanders, D. McKay, E. Chimenti, A. Meyer, N. Chafee, P. Butler, and E. Gibson; patent to be assigned to NASA.

However, the hydrogen reduction process is a clean operation and its chemistry is simple. For this reason and because hydrogen is the lightest weight reactant that could be transported from the earth to the moon, the process is being investigated at the Manned Spacecraft Center.

The simplicity of the process, the capability to use solar power, and the transportability of the equipment and initial reactants from earth on the presently conceived space-shuttle systems consign this process to a leading role as a batch process for making water from the lunar raw material.
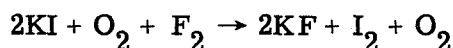
Fluorine-Exchange Process

Thermodynamically, all metal oxides should react with fluorine to liberate oxygen (ref. 3) and should form the corresponding metal fluorides in their highest valence states. Therefore, the conversion of lunar-surface fines by the use of free fluorine is an attractive process. Also, this conversion has the possibility of spontaneously combining most of the lunar-surface fines chemically with fluorine to produce oxygen. Any unspent fluorine and any oxyfluorides that might result are themselves excellent rocket-fuel oxidizers for hydrogen fuel. Currently, the process is being studied by NASA at the Manned Spacecraft Center and at the Lewis Research Center. The fundamental chemical reactions are as follows.

$$2Al_2O_3 + 6F_2 \rightarrow 4AlF_3 + 3O_2$$

$$SiO_2 + 2F_2 \rightarrow SiF_4 + O_2$$

$$2FeO + 2F_2 \rightarrow 2FeF_2 + O_2$$

$$TiO_2 + 2F_2 \rightarrow TiF_4 + O_2$$

The maximum operating temperatures are estimated to be approximately $773°$ K $(500° C)$. Theoretically, 45.4 kilograms (100 pounds) of lunar-surface fines must be reacted with 42.5 kilograms (93.5 pounds) of earth-supplied fluorine to yield 19.1 kilograms (42 pounds) of oxygen. From an economic standpoint, the fluorine must be recovered from the metallic fluorides and must be recycled. This is accomplished by reacting the fluorides with earth-supplied potassium; the reaction yields the free metals and potassium fluoride. The potassium fluoride may be electrolyzed by the use of solar power or nuclear-generated power to produce fluorine and potassium, both of which are recoverable for recycling in the process.

A sketch of the process is shown in figure 8. Purification of the oxygen for human consumption is achieved by passing the gas through a reversible bed of potassium iodide, according to the following reaction.
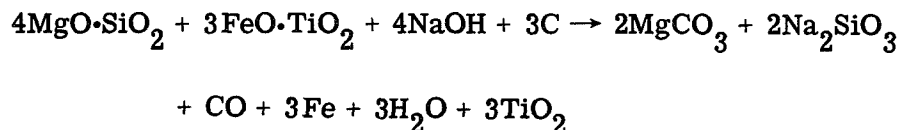
$$2KI + O_2 + F_2 \rightarrow 2KF + I_2 + O_2$$

Then, the potassium fluoride is electrolyzed, and the iodine is reacted with potassium to regenerate the potassium iodide bed.

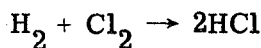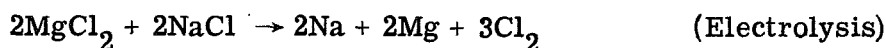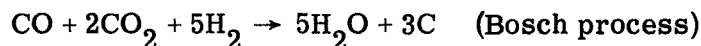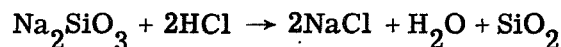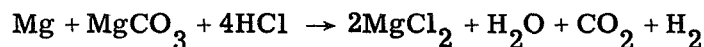Although the fluorine-exchange process may appear complicated, there are no recognized technological gaps. Automatic operation of the fluorine-exchange process in the vacuum environment of the moon appears simpler than it would be on earth, because of the absence of water vapor that induces fluorine corrosivity. The process has unique possibilities for large-scale operation for the production of oxygen and oxyfluorides. Economic success will depend on the reliable recovery of fluorine and potassium for recycling in the process, because these elements must be transported from earth originally.
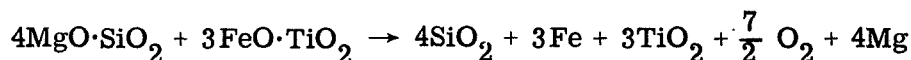
Carbonate/Oxygen Process

The preceding processes, two for making water and one for making oxygen from the lunar-surface fines, require the use of high temperatures (greater than 773° K (500° C)) and depend on reactions of the chemical agent either with molten lunar material or with hot surfaces to secure desirable reaction rates. The carbonate/oxygen process does not involve the use of high temperatures, and it lends itself to development of a continuously operating process rather than a batch-type process.

The carbonate/oxygen process involves the conversion of the lunar-surface materials to carbonates. This can be accomplished by mixing 38 percent by weight of lunar-surface fines with 38 percent by weight of sodium hydroxide and 24 percent by weight of charcoal. This mixture, when heated in a nickel container, dissolves the lunar fines. The carbon reacts to form carbon monoxide and carbonates; the carbon monoxide is collected as a gas. After reaction ceases, the matrix is allowed to cool and then is treated with earth-supplied hydrochloric acid. The acid produces chlorides of the metals and liberates gaseous carbon dioxide, which is combined with the carbon monoxide obtained in the first stages of the process. Then, the carbon oxides are passed through a Bosch reactor (fig. 6) using earth-supplied hydrogen. In the Bosch reactor, the carbon oxides are reduced to yield water and free carbon; the free carbon is recycled. The water is electrolyzed to produce oxygen and hydrogen. Also, the metal chlorides are electrolyzed to yield free metals and chlorine. Hydrogen from the water and chlorine from the chloride electrolysis are reacted to produce hydrogen chloride, which is recycled in the process. The chemical reactions are as follows.

$$4MgO \cdot SiO_2 + 3FeO \cdot TiO_2 + 4NaOH + 3C \rightarrow 2MgCO_3 + 2Na_2SiO_3$$

$$+ CO + 3Fe + 3H_2O + 3TiO_2$$

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$$Mg + MgCO_3 + 4HCl \rightarrow 2MgCl_2 + H_2O + CO_2 + H_2$$

$$Na_2SiO_3 + 2HCl \rightarrow 2NaCl + H_2O + SiO_2$$

$$CO + 2CO_2 + 5H_2 \rightarrow 5H_2O + 3C \quad \text{(Bosch process)}$$

$$2H_2O \rightarrow 2H_2 + O_2 \qquad \text{(Electrolysis)}$$

$$2MgCl_2 + 2NaCl \rightarrow 2Na + 2Mg + 3Cl_2 \qquad \text{(Electrolysis)}$$

$$H_2 + Cl_2 \rightarrow 2HCl$$

The overall reaction for reduction of lunar-surface fines by this process, assuming stoichiometric yields and recycling of products, is

$$4MgO \cdot SiO_2 + 3FeO \cdot TiO_2 \rightarrow 4SiO_2 + 3Fe + 3TiO_2 + \frac{7}{2} O_2 + 4Mg$$

In this equation, the lunar-surface-fines material is represented by the reactants.

Experimental work at the Manned Spacecraft Center is indicative of the chemical feasibility of the carbonate/oxygen process. The production of carbon dioxide and carbon monoxide from finely divided silicates by means of heating in the presence of alkali and carbon is straightforward. The conversion of these oxides to oxygen by use of the Bosch process is not as well known. In the Bosch process, carbon oxides and hydrogen are circulated through an iron catalyst at approximately $873°$ K ($600°$ C), until conversion of all of the oxygen to water has occurred. These reactions are as follows.

$$CO_2 + 2H_2 \rightarrow 2H_2O + C$$

$$CO_2 + C \rightarrow 2CO$$

$$CO + H_2 \rightarrow H_2O + C$$

$$2H_2 + C \rightarrow CH_4$$
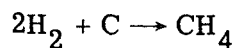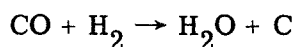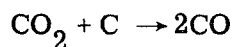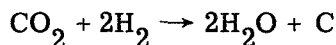
Not all of the carbon is converted to methane, and some free carbon remains as a product.

A study is yet to be made of the rates of carbon deposition in an iron-catalyzed Bosch reactor; the study would be used to determine the role of autocatalysis and to assess the activity of nonferrous materials and contaminants. As in the other reduction processes that have been described, the reliability with which the earth-derived reactants (such as carbon, sodium hydroxide, and hydrochloric acid) can be recovered will determine the economic suitability of the carbonate/oxygen process for use on the lunar surface.

Electrolytic Reduction

In the electrolytic reduction process, lunar-surface material is dissolved in sodium hydroxide by means of heating the alkaline mixture to approximately 673° K (400° C). As it is driven off, water is condensed and saved as a useful product. When the mixture is electrolyzed between pure-nickel electrodes, oxygen is obtained at the anode and sodium plates out at the cathode. However, the sodium immediately reduces the heavier metal oxides and silicates in the molten matrix and releases these metals while continuously producing oxygen at the anode. The electrolyte may be "salted" with small amounts of sodium fluoride, which lowers the cell temperature and aids in separating the metals. Fluorine, which forms at the anode, reacts with the melt to produce oxygen, which escapes from the cell. The process is similar to the one that is used for the electrolytic production of aluminum. On earth, the metal is valuable and is retained, whereas the oxygen escapes; on the moon, the oxygen would be valuable and would be retained, and the metal possibly would be discarded. Chemical-engineering technologies which have proved efficient in making aluminum on earth appear to be applicable to the production of oxygen on the moon.

Theoretically, 8 grams of oxygen can be produced for every 96 500 coulombs that are used to dissociate lunar fines in an electrolytic cell. This is equivalent to the use of approximately 30 ampere-hours of current to yield 8 grams of oxygen, or the use of 13 300 ampere-hours to produce 3.63 kilograms (8 pounds) of oxygen. At 1-volt potential, this is equal to 13.3 kilowatts. If it is assumed that the cell is 67-percent efficient, then 0.453 kilogram (1 pound) of oxygen requires the use of 2.5 kilowatts. One man consumes approximately 0.745 kilogram (1.64 pounds) of oxygen daily; 4.1 kilowatts would be needed to produce this much oxygen by this process. An electrolytic cell that requires 25 kilowatts to produce 4.535 kilograms (10 pounds) of oxygen per day (sufficient for 6 men) weighs approximately 208.6 kilograms (460 pounds). A solar array that could produce 25 kilowatts weighs approximately 1500 kilograms (3300 pounds). Thus, the oxygen requirements for 6 people on the moon may be provided by approximately 1720 kilograms (3800 pounds) of power-generation and electrolysis equipment.

In the processes just described, electrolysis is needed to produce products that must be recycled to establish economic feasibility. However, the electrolytic reduction process involves electrolysis as the principal reaction. On the moon, electrolytic reduction may be carried out on a large scale with solar or nuclear-derived electrical energy.

OXYGEN STORAGE ON THE MOON

.For oxygen to be useful on the moon or on a planet, the oxygen must be stored in such a manner that it will not dissipate before use and so that it can be reclaimed easily as needed. Cryogenic storage systems involve pumps that are complicated and fragile. However, the storage of water or ice as a source of oxygen appears to be feasible, because the oxygen in water can be extracted as needed by electrolysis of either the liquid or the vapor. Nevertheless, studies of the long-term storage and transportation of fluids need to be made so that the design engineer can choose high-pressure gas storage, solid-chemical storage, or cryogenic storage systems. A new field of chemistry and chemical engineering research exists in oxygen storage systems, and radically new ideas on how to store oxygen may prove fruitful. For example, knowledge on how to stabilize alkaline earth ozonides, such as CaO_4 (ref. 4), might be indicative of the feasibility of manufacturing ozonides on the moon. Oxygen would be derived simply by heating the ozonides. Alternatively, oxygen complexes (pseudocompounds of oxygen that are solids which are much more stable than solidified oxygen itself) hold promise for being efficient forms in which oxygen might be stored (ref. 5). Engineering studies designed to reveal and assess possibilities of complex oxygen systems are required.

CONCLUDING REMARKS

Five potential chemical processes for making oxygen for human use on the moon have been considered. These processes are a carbothermic process, a hydrogen reduction method, a fluorine-exchange technique, a carbonate/oxygen conversion process, and an electrolytic reduction method. Studies on a laboratory-bench-scale basis indicate that these five processes presently appear to be feasible technically and suitable for detailed assessment. Potentially, all five methods are worthy of engineering development because each method has unique characteristics that are susceptible to product-use requirements, environmental influences, electrical-energy availability, and reactant-supply logistics. For instance, two of the processes, the carbothermic process and the hydrogen reduction process, involve the use of thermal inputs that are sufficiently high to produce molten minerals. These methods are especially suited for batch-type operations. Moreover, water is the primary product, and by electrolysis of this water, oxygen of exceptional purity may be derived. However, the fluorine-exchange process yields oxygen directly and in large quantities; this process probably is best suited for the production of oxygen for use as rocket fuel. Finally, the last two processes, the carbonate/oxygen conversion method and the electrolytic reduction process, are relatively-low-temperature methods that result in breathing-quality oxygen. The electrolytic reduction process is capable of conversion to continuous operation on the lunar surface.

The basic chemistry in each of these processes is straightforward. Based on the results of the Apollo 11 and 12 lunar-sample analyses, the primary lunar resource is an abundance of surface material of fairly uniform particle size for which the physical and chemical properties now have been identified. Currently, the weight penalties for electrical-power-generation equipment and electrolysis cells are quite severe and must be minimized. Ultimately, it is expected that manned colonies are to be established on the moon; only then will the unique properties of the moon truly be available for scientific and practical purposes. Man's ability to stay, live, and work on the moon or on other heavenly bodies of the universe depends upon the successful development of a process for the extraction of oxygen and water from the lunar-surface materials.

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National Aeronautics and Space Administration
Houston, Texas, June 17, 1971
914-50-20-21-72

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5. Ruehrwein, R. A.; and Hashman, J. S.: U. S. Patent 3,378,351 to the United States of America, Secretary of the Army, Apr. 16, 1968.

TABLE I. - OXIDE COMPOSITIONS DETERMINED BY THE USE OF

X-RAY FLUORESCENCE AND EMISSION-SPECTROSCOPY DATA

Oxide	Sample source	
	Hawaiian basalt, weight percent	Ilmenite, weight percent
SiO_2	49.6	4
Al_2O_3	14.7	2.8
FeO	11.5	52
MgO	7.5	3.6
CaO	11.0	.7
TiO_2	2.8	35
Na_2O	2.1	<.1
K_2O	.6	<.1
MnO	.2	.12
Total	100.0	98.42

TABLE II. - COMPARATIVE ANALYSES OF THE APOLLO 11

AND THE SIMULATED LUNAR-SURFACE FINES

Oxides	Sample source	
	Apollo 11, weight percent	Simulated fines, weight percent
SiO_2	42.0	46.1
Al_2O_3	14.0	13.8
FeO	15.8	13.0
Fe_2O_3	--	1.7
MgO	8.0	7.2
CaO	12.0	10.3
TiO_2	7.6	5.3
Na_2O	.44	1.9
K_2O	.13	.5
MnO	.21	.2
Total	100.18	100.0

Figure 1. - Lunar surface material returned from the Apollo 11 mission (size range: 1 to 3 millimeters across).

Figure 2. – Enlarged view of thin section of particle of lunar fines, showing crystals of plagioclase (large), olivine (small), and dark masses of glassy matrix.
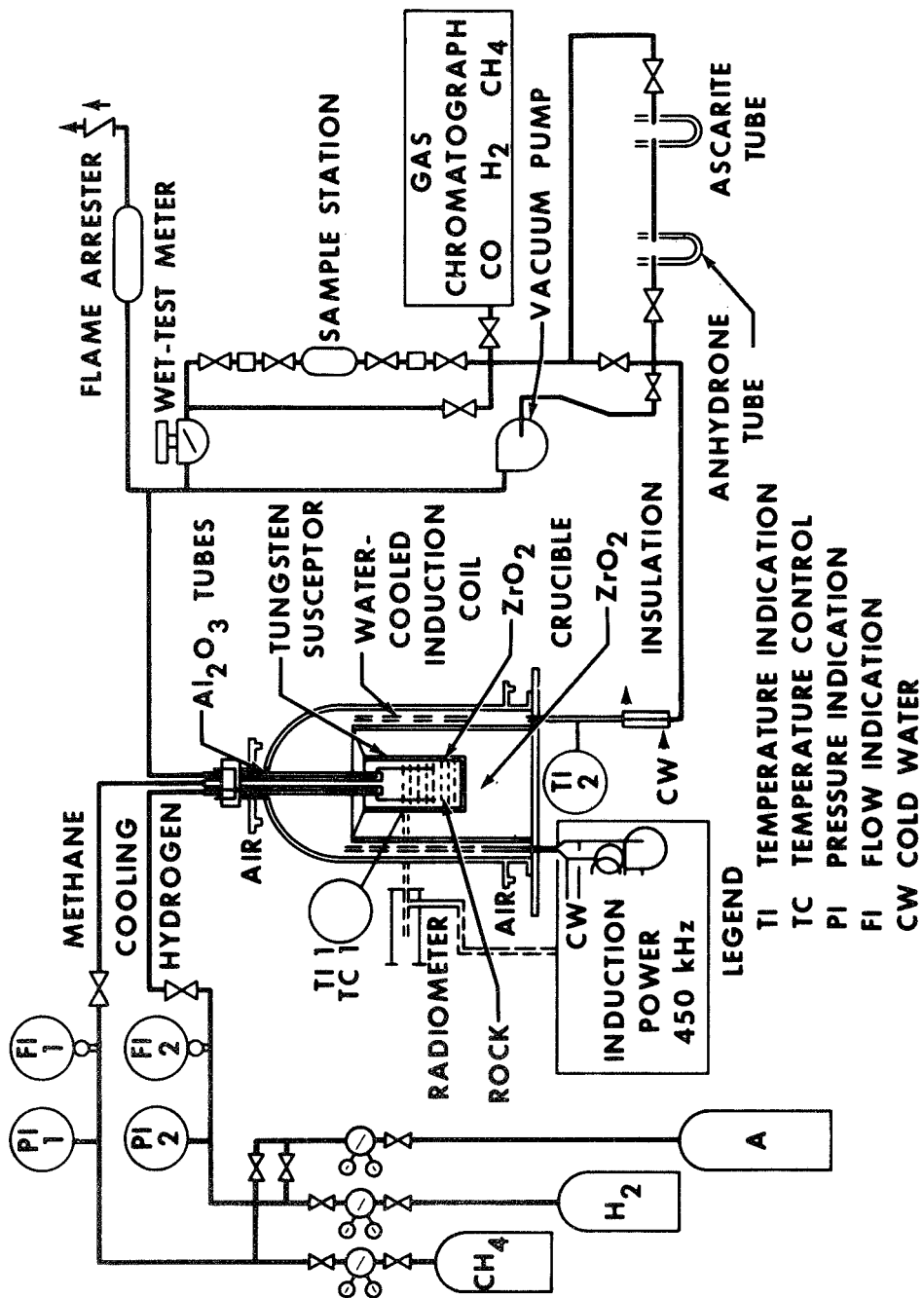
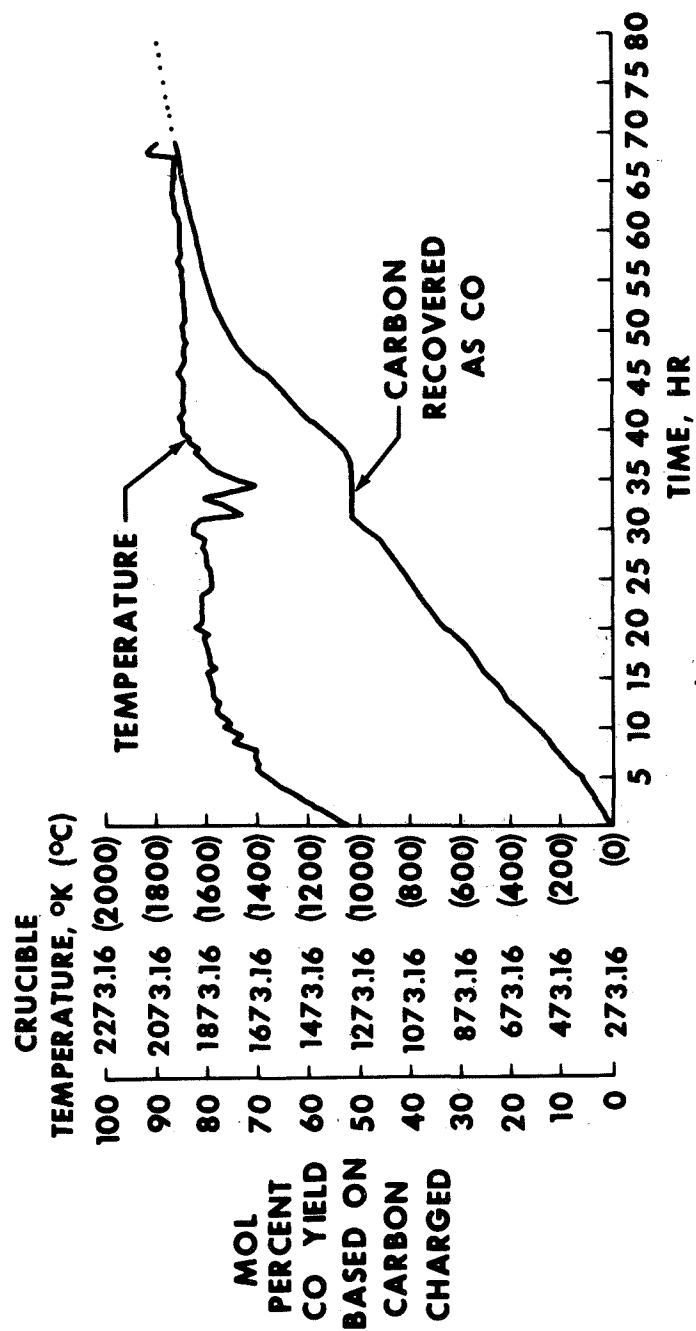Figure 3. – Carbothermic process test arrangement.

Figure 4. - Carbon recovery from basalt reductions expressed as a function of time.
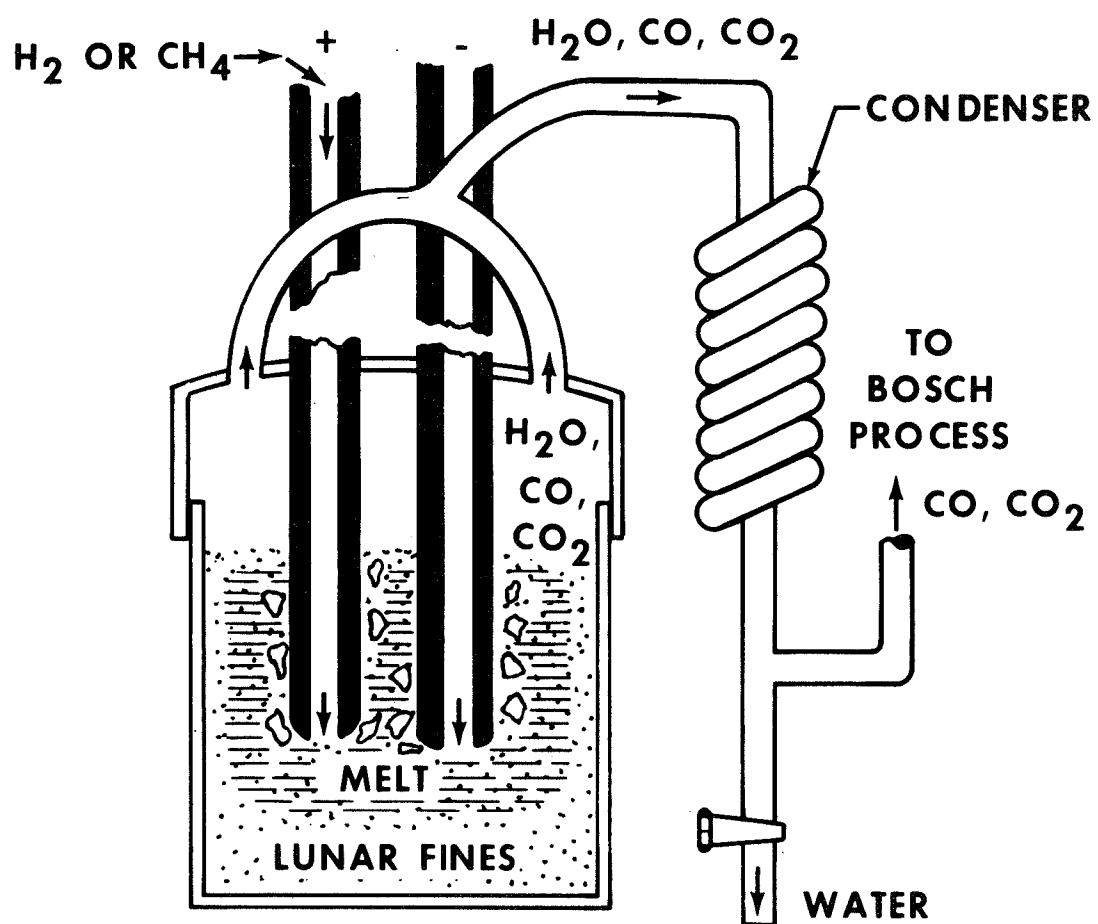
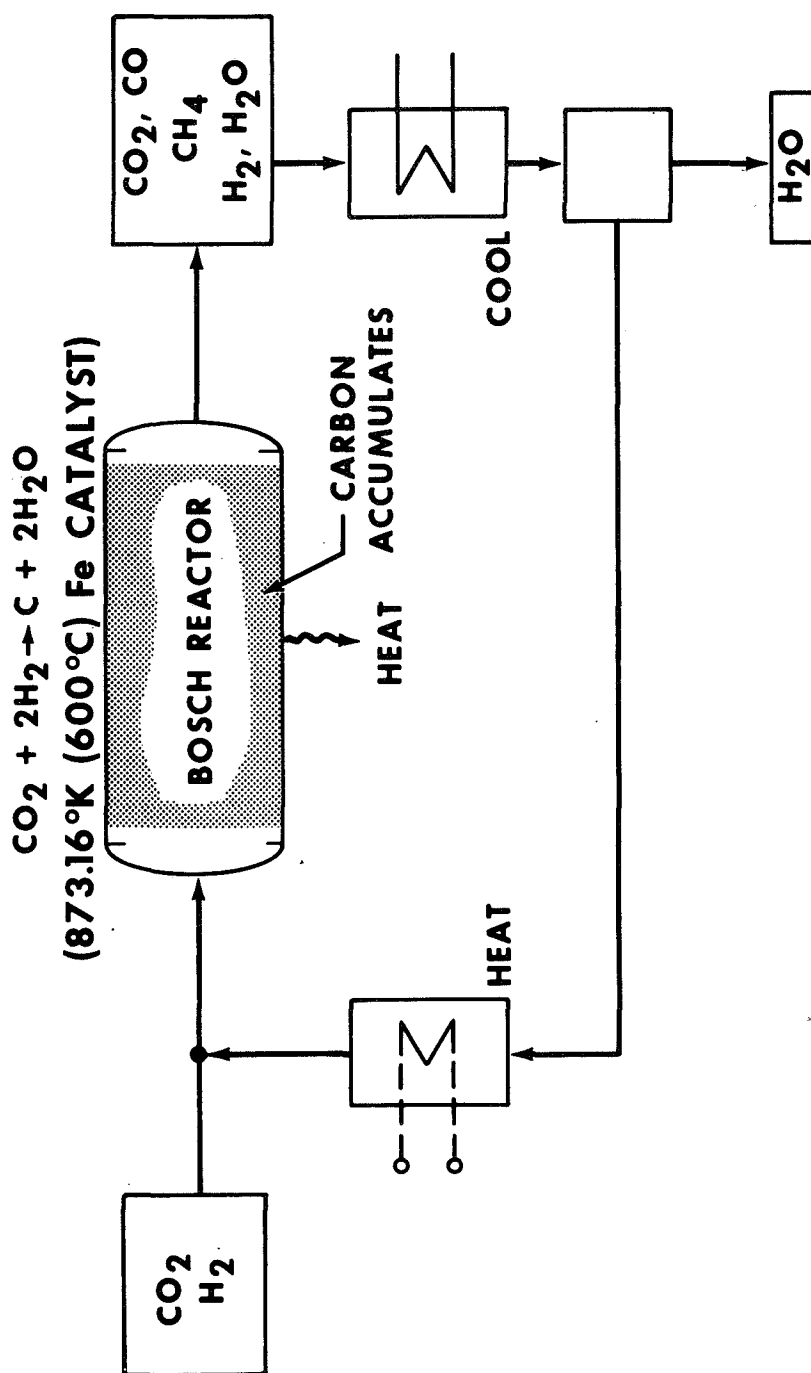Figure 5. – Carbothermic reduction in an electric-resistance furnace.

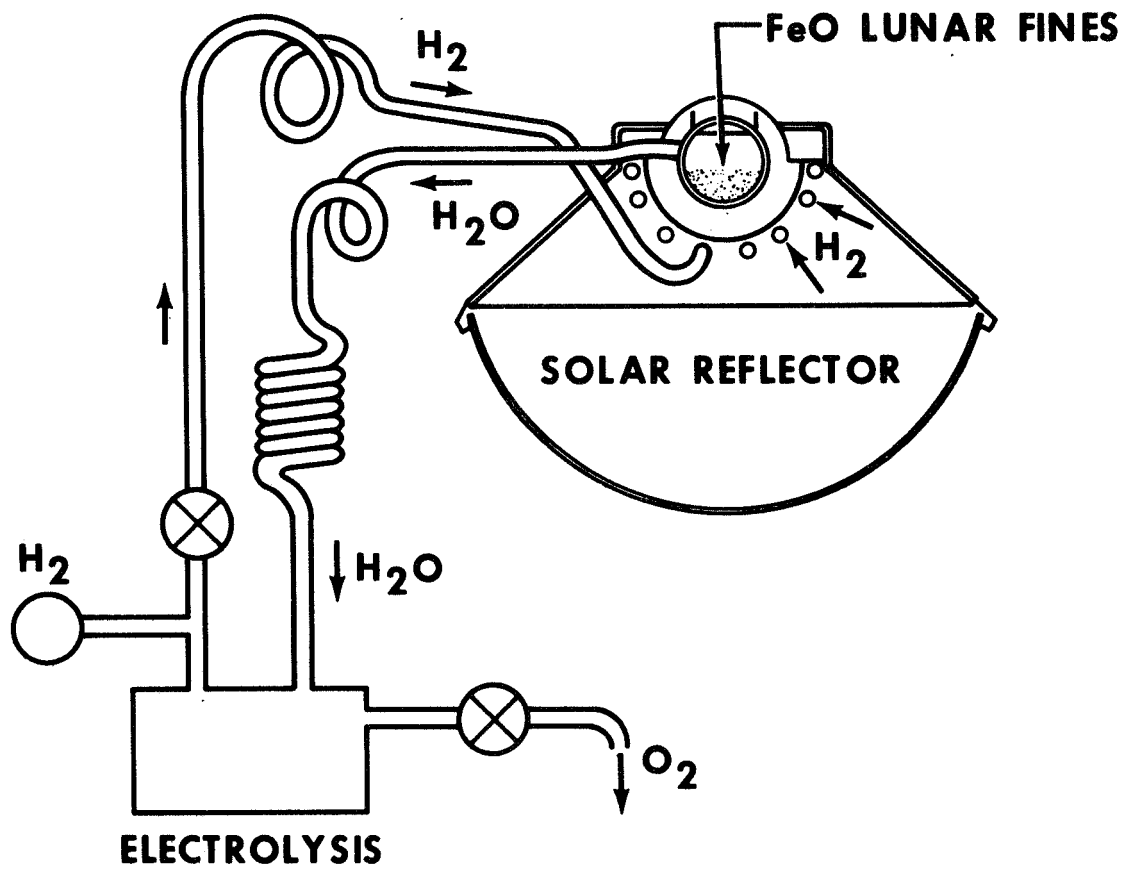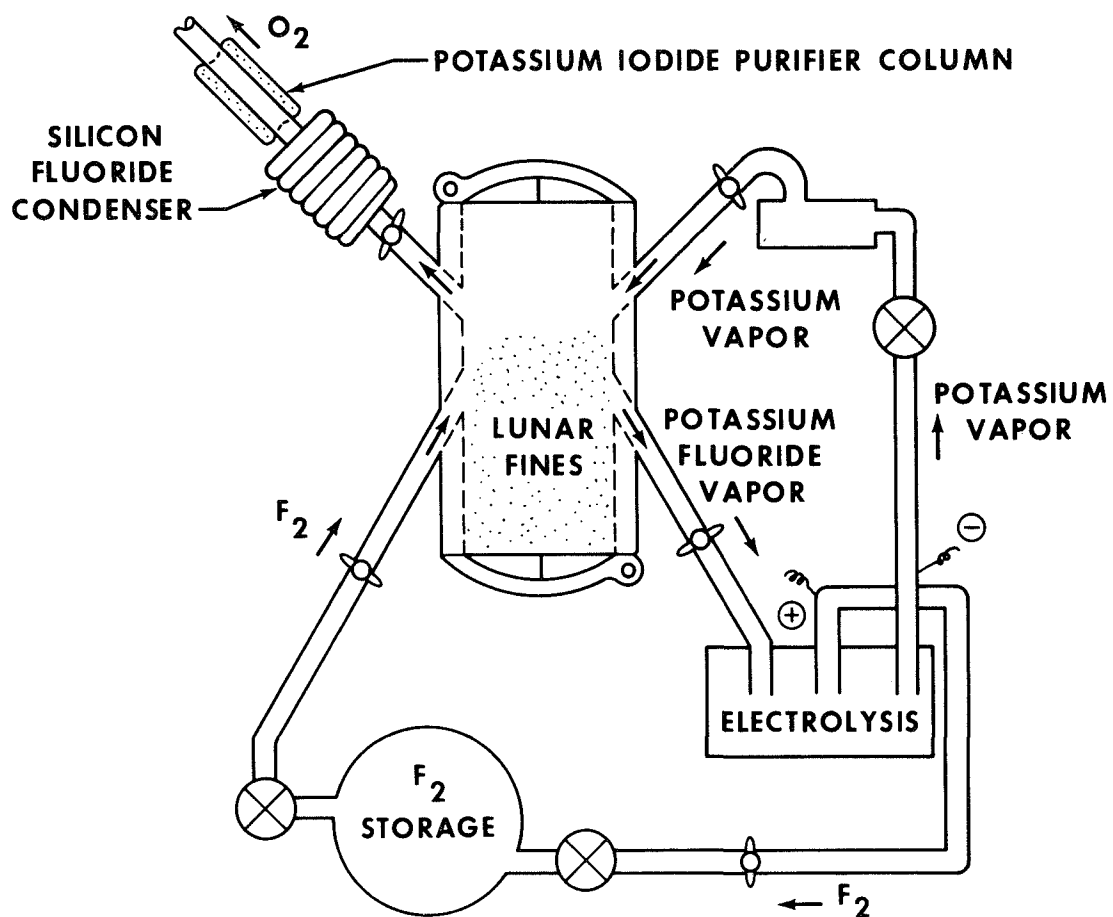Figure 6. - Diagram of the Bosch process.

Figure 7. - The hydrogen reduction process.

Figure 8. - The fluorine-exchange process.